Optimization of Fatigue Strength of Welded Rotationally Symmetrical Components by Surface Strengthening of Welding Zone

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1. Summary

Dynamic component tests are integral part of innovative development projects in numerous application ranges of automotive supply industry. In this contribution comparative studies of so-called ball studs (Fig. 1) are put up for discussion. Emphasis of analysis refers to rotationally symmetrical welded components. By the use of destructive material testing new findings should be gained in order to optimize durability of ball studs in consideration of economical issues. Components have been tested to failure by means of high frequency pulser.

![Figure 1: Ball stud as a model and in original, welded design](image1)

The fracture patterns (Fig. 2) show in all cases a crack propagation, which propagates from the weld zone into the cone. Mechanical methods for processing of the welding zone, for example by compaction rolls, as well as abrasive processes with subsequent polishing or blasting of the surface yielded not a positive result in terms of an increase of load. Only through a process of an additional hardening the surface of the welding zone could improve the number of load cycles by a factor of 8-10.

![Figure 2: Fracture patterns of welded ball stud](image2)
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2. Introduction

The main applications of the tested ball studs are car-coupling rods (Fig. 3), which connect the stabilizer to the suspension strut.

![Figure 3: Example of a coupling rod [5] with ball stud](image)

By default, ball studs are produced by cold forming of the blank followed by further processing. The first step of post-processing is a shape turning process to get the final contour of the ball stud. The second step is a surface treatment process i.e. ball is work hardened by spinning operation and roughness is reduced. Further still notch effects are present by the machining shape in the transition region between the ball and the shaft. Notching effect generally has a negative influence on flexural fatigue. Due to increased demands in recent years in terms of design and load of ball studs, the question arose how to increase the number of cycles with unchanged geometries. After numerous tests, e. g. with high-tensile materials, work hardening of the welding zone or abrasive operations followed by polishing respectively blasting of the surface did not increase life time. Aim of the project was to develop a method realizing increase of life time of ball studs with specified geometry and flexural fatigue.

3. Fundamentals and Experimental procedure

As described in chapter 1, ball studs are manufactured by a cold forging process followed by several processes like turning, grinding and polishing. An alternative manufacturing process is the production of the base body by cold forging followed by a welding process, in which a ball of the base body is welded. The benefits of the welded version are better roughness of ball surface and the needlessness of post-machining, because basic bodies as well as the ball already have their final shape. Since more than ten years ball studs in welded version have been successfully applied. Increasing customer requirements within the scope of several „Downsizing“– projects forced the geometrical boundary conditions to be adapted. Regardless of the geometric changes, for example a smaller ball diameter and / or smaller shaft design, the load requirements are increased. For these reasons a project has been initiated in order to compile a feasible and economical solution.
4. Typical stress type for ball studs

Ball studs usually are subjected by bending. This means that, first and foremost bending forces may be applied. Theoretical calculations based on the FKM or DIN 743 and a first fracture mechanics analysis of stress intensity factors have shown that the example of our welded ball stud meets the criterion for a crack growth. The result of the calculations [1-4] shows that $\Delta K > \Delta K_c$, which explained a crack growth. Hereinafter, the test results are displayed, showing the results available for the required load. For test procedure a high-frequency pulser from „Zwick-Roell“ is used. Frequency of pulser is between 50 and 70 Hz. Fig. 4 shows the fixing unit for seating the specimen.

![Figure 4: Pulser with ball mount for the simulation of a coupling rod connection](image)

5. Experimental Procedure

The first test run has been conducted for ball studs with a reworked welding zone. The rework has been considered purposeful in order to reduce the notching effect in the weld zone’s transition area between ball and stud. The Customer’s requirement was a repeated load of $\pm 2,5$ kN with a stress ratio of $R = -1$ and at least 200,000 load cycles. Figure 5 (right hand side) is showing the numbers of cycles to failure of the tested ball stud. The individual cycles results were then transferred into a Weibull (Fig. 5, left). Subsequently the specific load cycle results have been transferred into a Weibull diagram (Figure 5 left hand side).

![Figure 5: Weibull and experimental results with turned and polished welding zones](image)
The requirement of at least 200,000 load cycles has not been fulfilled. Now it was necessary to think about further options to increase the fatigue strength of the ball studs. The result was the utilization of residual compressive stresses in the transition area between the ball and the shaft. The hardening of the edge layer, especially in the welding zone area, has been realized by induction hardening (Fig. 6). Alternative processes like laser hardening or nitrogen hardening were out of the question either for financial or for technical reasons.

Figure 6: Result of inductive surface hardening (discolor the ball (left), model the heat affected zone (center), cut (right))

In an additional step the measurement of micro hardness of heat affected zone has been conducted in order to evaluate ratio between edge layer hardness and core hardness. On the left hand side on figure 7 shows the result of measured position. On the right hand side on figure 7 illustrates the results of micro hardness measurement; edge layer area ≈ 550 HV; core area ≈ 350 HV.

Figure 7: Grid and hardness profile of the heat-affected zone

The edge layer hardened samples of ball studs have been tested with a high frequency pulser (2.5 kN 3.0 kN 3.5 kN, 4 kN) according to required test load data. Because of the non-successful load cycles results, in accordance with customer requirement of ±2.5 kN for ball studs with additional turning process of the welding zone, now edge layer hardened ball studs were tested with a load of ±2.5 kN.
Results of the initial test series are represented for comparison in table 1.

Table 1: Comparison of cycles "with additional turning process " and "Surface hardened"

<table>
<thead>
<tr>
<th>Cycles</th>
<th>Cycles</th>
</tr>
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<tbody>
<tr>
<td>with additional turning process</td>
<td>surface hardened</td>
</tr>
<tr>
<td>1</td>
<td>69,290</td>
</tr>
<tr>
<td>2</td>
<td>70,060</td>
</tr>
<tr>
<td>3</td>
<td>73,240</td>
</tr>
<tr>
<td>4</td>
<td>73,525</td>
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<tr>
<td>5</td>
<td>97,280</td>
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<tr>
<td>6</td>
<td>104,380</td>
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<td>7</td>
<td>108,015</td>
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<td>8</td>
<td>109,380</td>
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<tr>
<td>9</td>
<td>113,800</td>
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<tr>
<td>10</td>
<td>146,525</td>
</tr>
<tr>
<td>11</td>
<td>164,460</td>
</tr>
<tr>
<td>12</td>
<td>165,800</td>
</tr>
</tbody>
</table>

For specified load of ± 2,5 kN there was no failure of components of edge layer hardened ball studs. The test series have been stopped correspondingly between one million and five million cycles. Individual results of ball studs with reworked welding zones as well as the results with edge layer hardened ball studs have been subsequently transferred into a Weibull- and Wöhler diagram. The Weibull-Diagram of the survival probability of edge layer hardened ball studs in comparison with ball studs without surface hardening (Fig. 8) shows that the survival rate was improved by the factor 10. By way of example we regard the range ± 3,5 kN (survival probability SP, grey and black line), illustrating this increase of load from 20,000 cycles to 200,000 cycles. According to Weibull-diagram the Wöhler-diagram in Fig. 9 also indicates a considerable improvement regarding fatigue strength under repeated load.

Figure 8: survival probability Weibull-diagram, comparison of ball studs without surface hardening (black line)/with surface hardening (gray line)
6. Conclusions and Outlook

In a further step the behavior of edge layer is to be analyzed by means of additional mathematical calculation and a FEM simulation of the welding zone. Furthermore the dependency between the material, edge layer hardness/core hardness, depth of the edge layer hardening and the diameter ratio of the samples is to examined more closely. With this technical approach it should be possible to create an optimal design as a function of boundary conditions for similar products. Further tests are planed as well with aluminum casting parts to identify the properties of the welding zones in these parts and to improve the lifetime.

7. References

[1] Theilig, H; Nickel, J; Spannungsintensitätsfaktoren; VEB Fachbuchverlag, Leipzig; 1. Auflage; 1987